Airborne Imaging Fabry-Perot Interferometer System for Tropospheric Trace Species Detection: IIP Project Update

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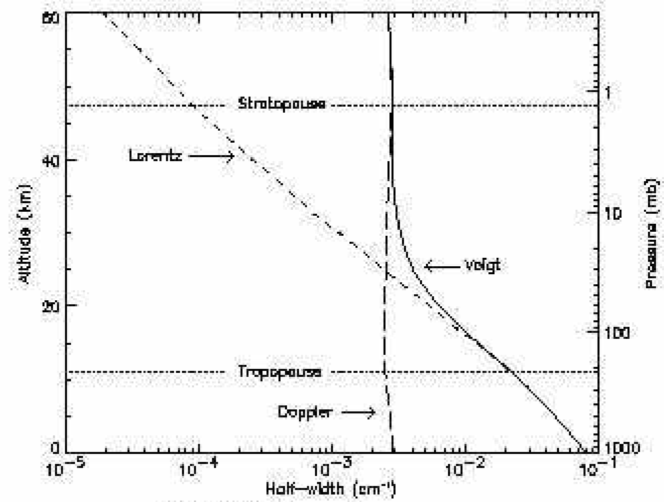
-> Topics:

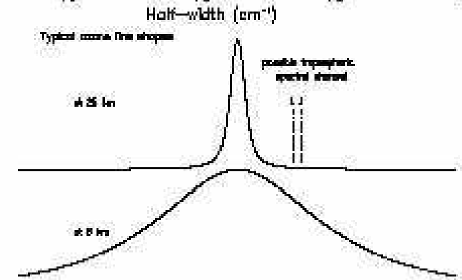
Scientific Motivation
Measurement/Instrument Concepts
TTSS-FPI (IIP) Program Summary
Progress-to-date

Science Motivation

- **Tropospheric chemistry identified as key measurement area for future NASA Earth science missions (*NASA OES Strategic Enterprise and Science Research Plans*)**
- **Tropospheric ozone (O_3) clearly recognized as one of the most important gas phase trace constituents in the troposphere**
  - **key oxidant in tropospheric photochemistry;** O_3 photolysis is one of the principal sources of the hydroxyl radical (OH), the most important radical species associated with the photochemical degradation of anthropogenic and biogenic hydrocarbons
  - **exposure to enhanced levels negatively impacts health, crops, and vegetation;** O_3 is responsible for acute and chronic health problems in humans and contributes toward destruction of plant and animal populations
  - **greenhouse gas;** contributes toward radiative forcing and climate change
  - **Levels have been increasing and will continue to do so as concentrations of precursor gases (oxides of nitrogen, methane, and other hydrocarbons) necessary for the photochemical formation of tropospheric O_3 continue to rise;** there is evidence suggesting that average surface O_3 concentrations may have doubled over the last century
- **Space-based detection of tropospheric ozone critical for enhancing scientific understanding & lessening impacts of exposure to elevated concentrations**
  - **spatially heterogeneous & high levels are not unique to urban areas;** non-uniform sources/sinks & transport; enhanced tropospheric O_3 observed over the south tropical Atlantic Ocean

Measurement & Instrument Concepts





- **[Measurement Concept]**: Spectrally isolate pressure-broadened wings of strong 9.6 micron ozone lines to enable tropospheric ozone mapping from a geostationary-based platform
  - continuous day/night coverage independent of solar zenith angle
- **[Instrument Concept]**: Spatially imaging double-etalon FPI system
  - LRE, HRE, & ultra-narrow filter in series configuration
  - spatial imaging with advanced FPA
  - active control loop for spectral tuning and parallelism control

FPI (high throughput & spectral resolution) + Double-etalon configuration (single-order transfer fcn) + GEO-based imaging system (high space & time resolution; maximize SNR) → **Spectral isolation capability; minimize undesirable signal contributions** (interferant species, surface, & clouds)

Etalon Characteristics

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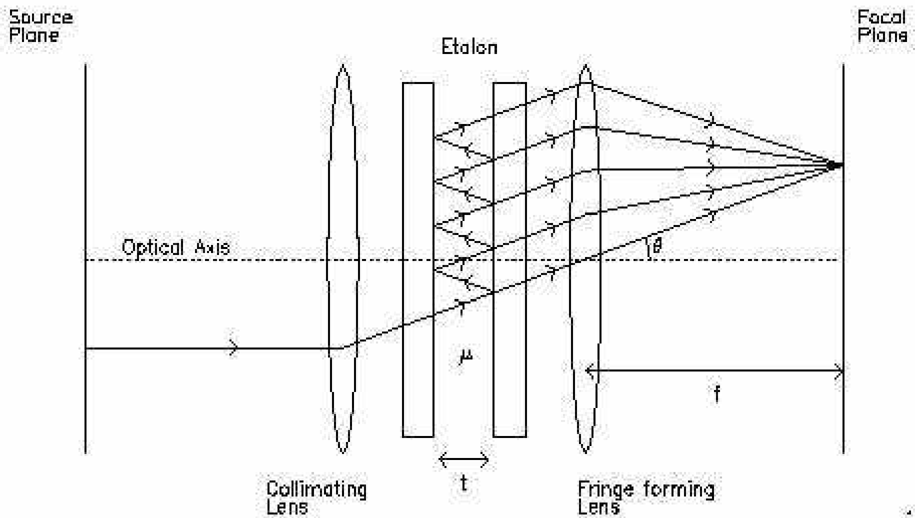
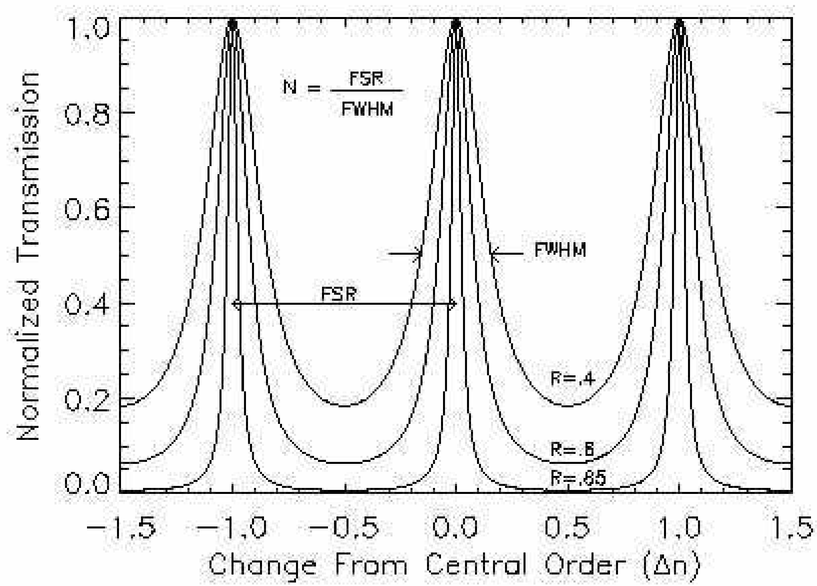
Monochromatic Ray Propagation Through Simple FPI



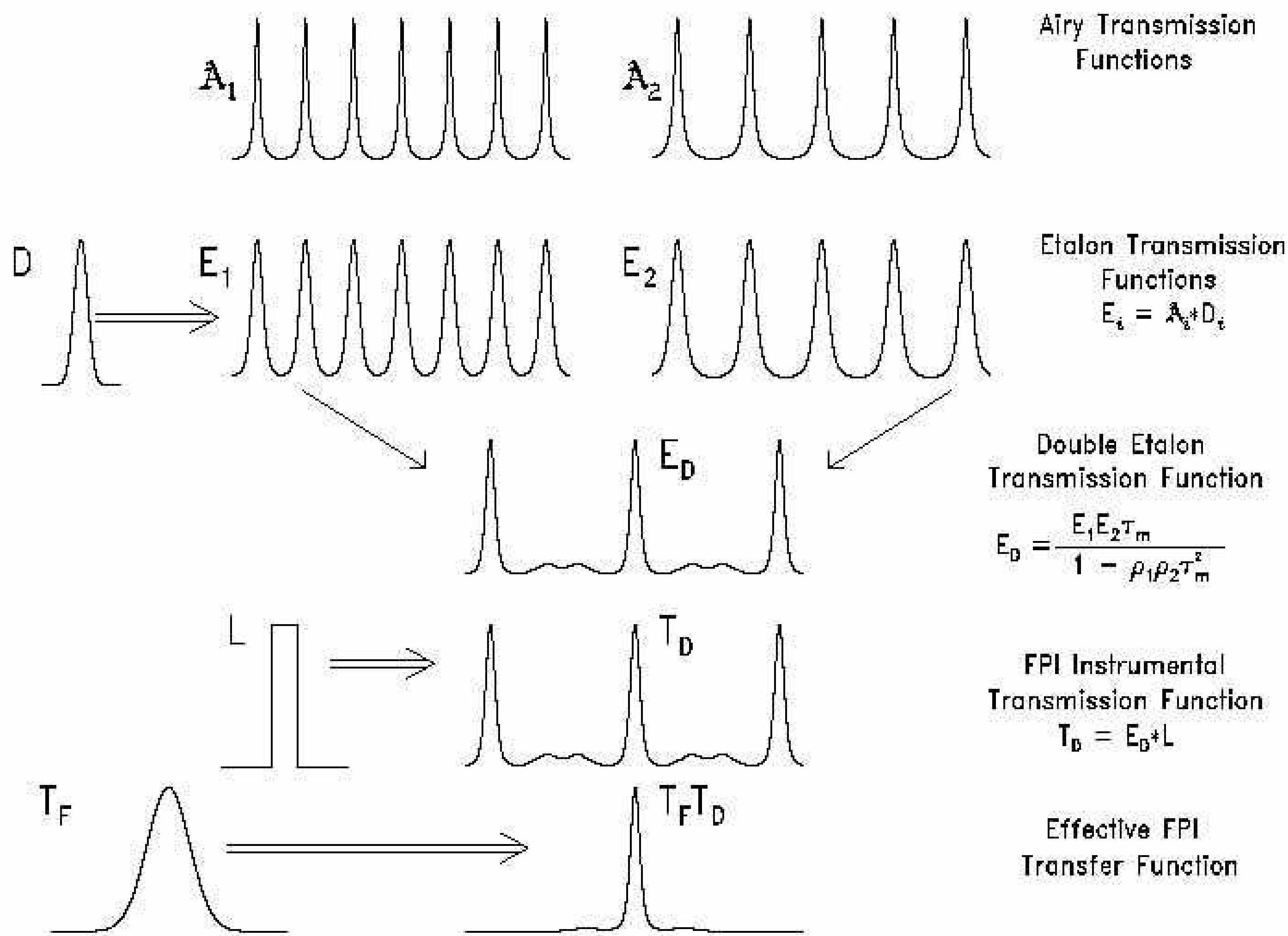
- *Constructive interference produces transmission maxima at resonant wavelengths, yielding periodic transmission function*
- *Additional etalons can be added in series to eliminate unwanted passbands, improve sideband rejection, and extend the effective FSR*

- *Acquire spectral information by tuning spectroscopic variables: mechanical (t), pressure (u), and spatial (or angular, theta) scanning*
- *Spectral & spatial variability across focal plane for imaging configuration*

Airy function (ideal etalon) transmission



Formation of Single-Order Double-Etalon Transfer Function



Spectral Dependence of DE-FPI Transmission vs. Off-axis Position

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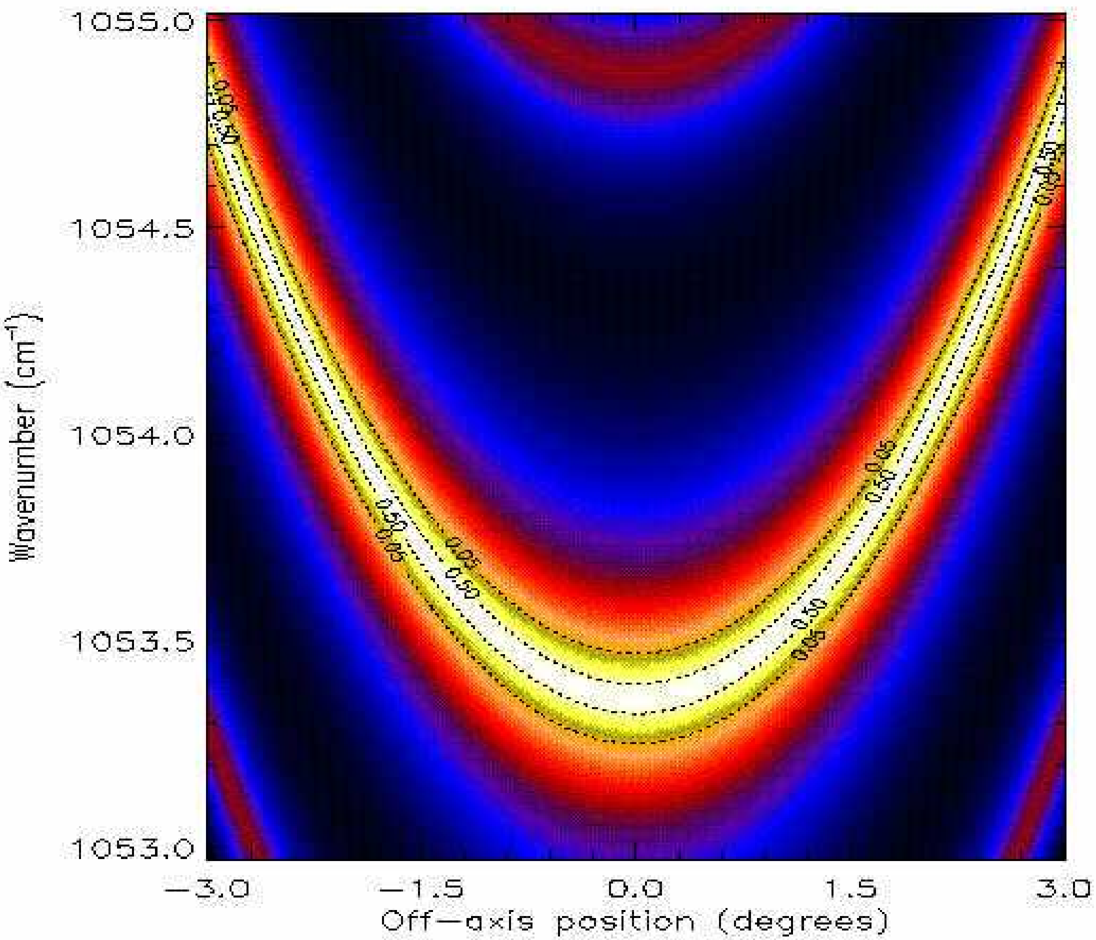

Log(T) shown

ESTO Instrument Incubator Program

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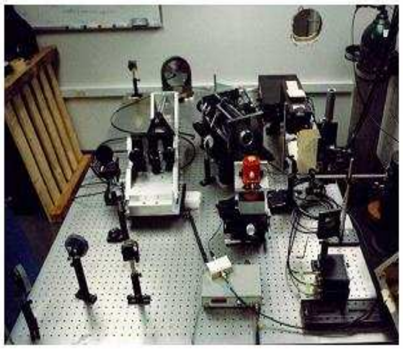
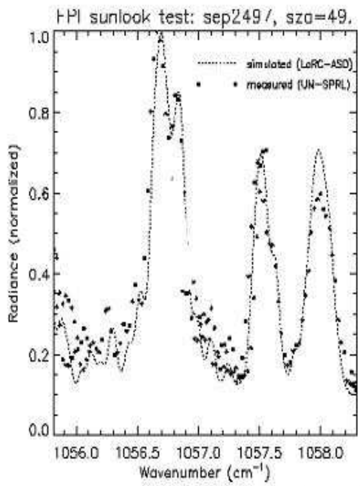
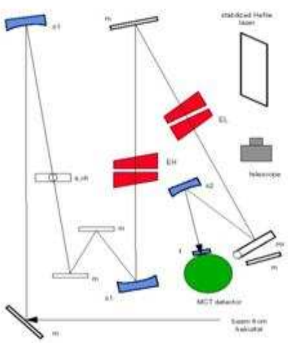
Tropospheric Trace Species Sensing Fabry-Perot Interferometer (TTSS-FPI)

Heritage

Laboratory Breadboard







- Measurement technique demonstrated for non-imaging, ground-based solar absorption measurements
- Further validation needed: nadir-viewing emission measurements in imaging configuration, with autonomous operation; mitigate risk for infusion into future space-based science missions

Participants

- **Principal Investigator: Dr. Allen Larar, NASA-LaRC**
- Co-Investigator: Dr. William Cook, NASA LaRC
- Co-Investigator: Dr. Jeffery Puschell, Raytheon SBRS
- Co-Investigator: Dr. Wilbert Skinner, Univ. of Mich.
- Science Collaborator: Dr. William Smith, NASA LaRC

Program Focus

Objective is to develop and demonstrate from an airborne platform an advanced atmospheric remote sensor concept intended for geostationary-based measurement of **tropospheric O_3,** with applicability toward other trace species (eg., CO, CO_2, & N_2O)

Four key TTSS-FPI IIP elements: 1) develop **airborne instrument** prototype, 2) perform demonstration **flight operations** on high-altitude aircraft, 3) process and **analyze** flight engineering & science **data**, and 4) define a **spaceflight sensor concept**.

Major Milestones & Infusion

Milestones

- < 3-Year Proposed Duration (FY02 – FY05)
- Mar 02 – Program Start
- Nov 03 – Airborne System Definition and Design Complete
- Nov 03 – Parts Procurement & Fabrication Complete
- Apr 04 – Sensor Integration, Calibration, and Lab Testing Ends
- Sep 04 – Complete Field Demonstration & Analysis
- Oct 04 – Space-based Instrument Design Studies Complete
- Nov 04 – Complete Final Report

Potential Applications / Missions

- NMP, ESSP, EOS, NPOESS, GOES

TTSS-FPI Integrated Sensor Demo Approach
–piggyback flight with validated airborne sounder

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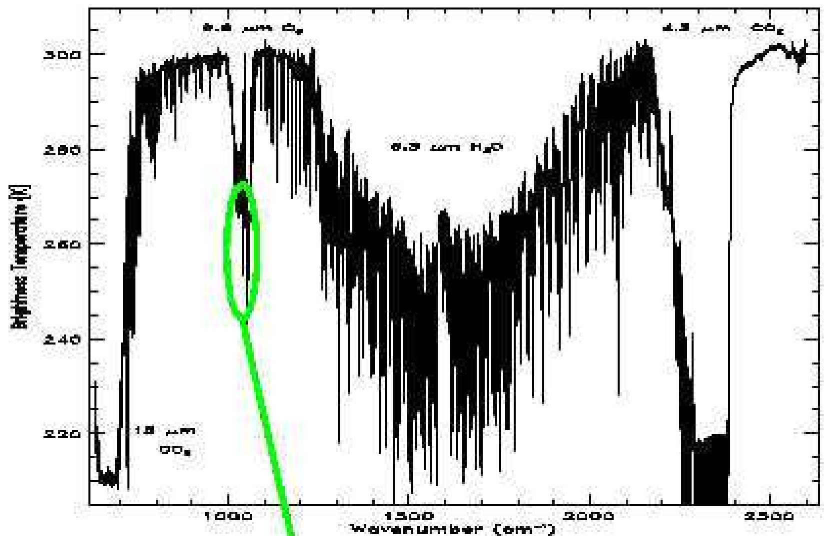
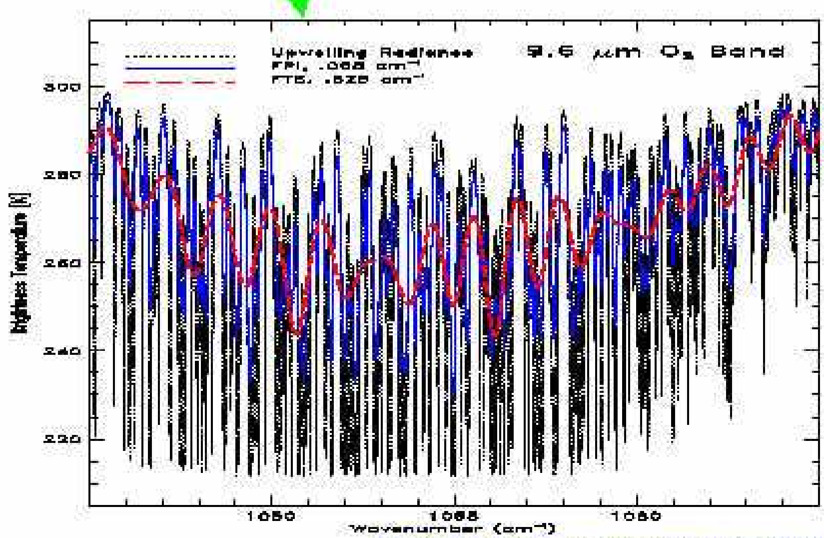


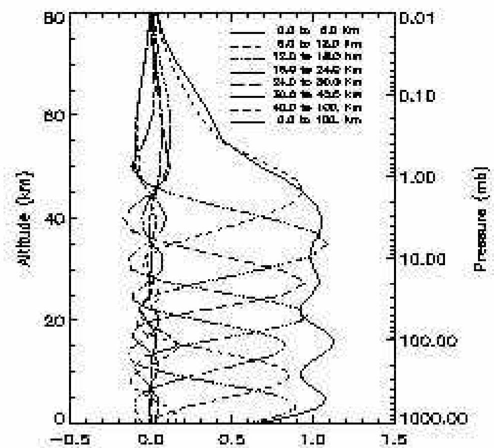
Lower-resolution advanced sounder (FTS) spectrum (**NAST-I**)

T(p), H_2O(p), T_S, Es

Higher-resolution **FPI** spectrum

retrieval

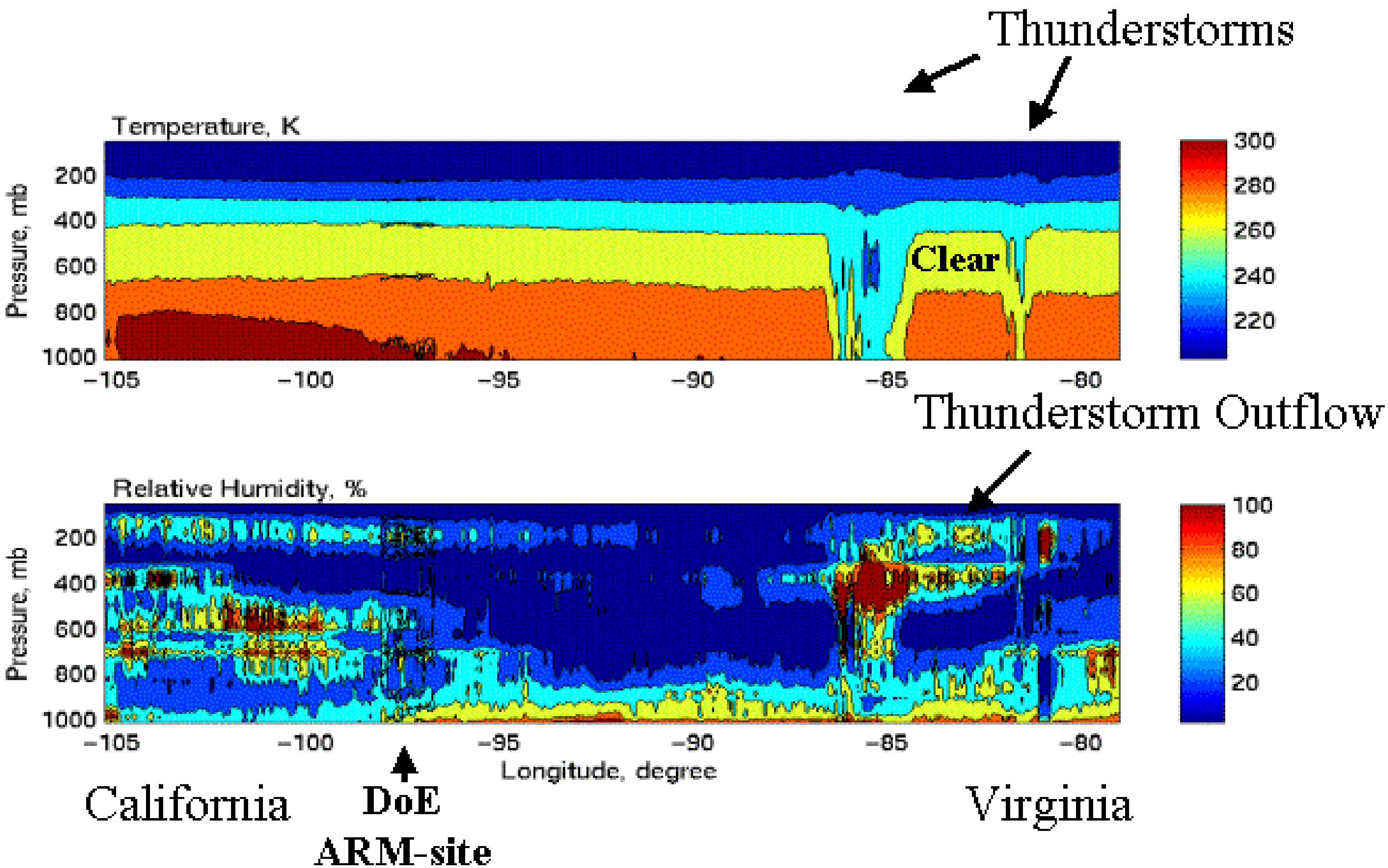




Tropospheric

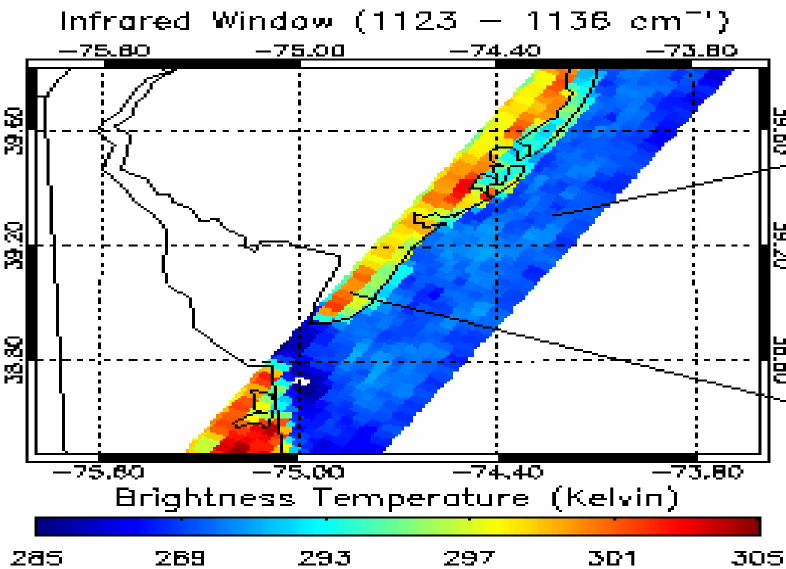
O_3

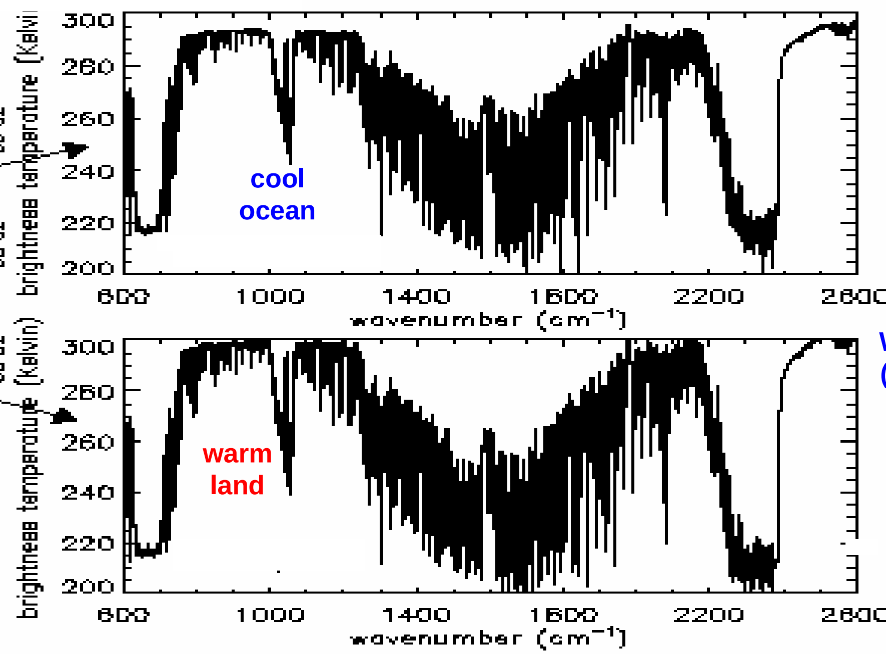
NAST-I Cross-country Cross-section: WFF (VA) to DFRC (CA)--Aug. 27, 1999



NAST-I Observes 3-Dimensional Structure

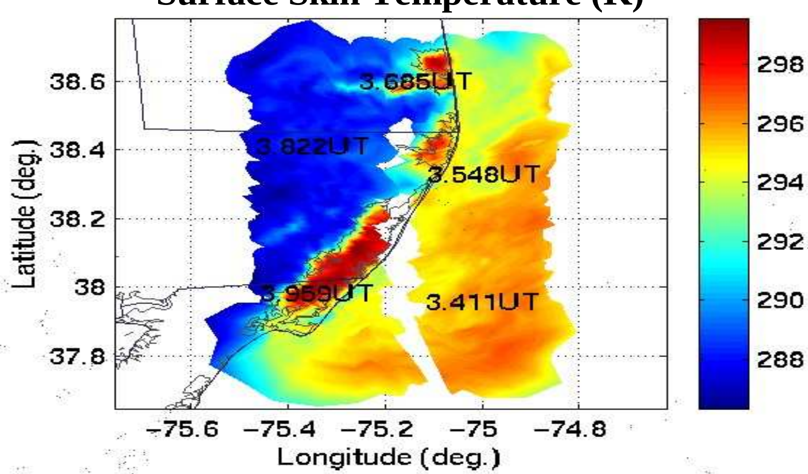
with High Spatial/Spectral Resolution and Radiometric Accuracy



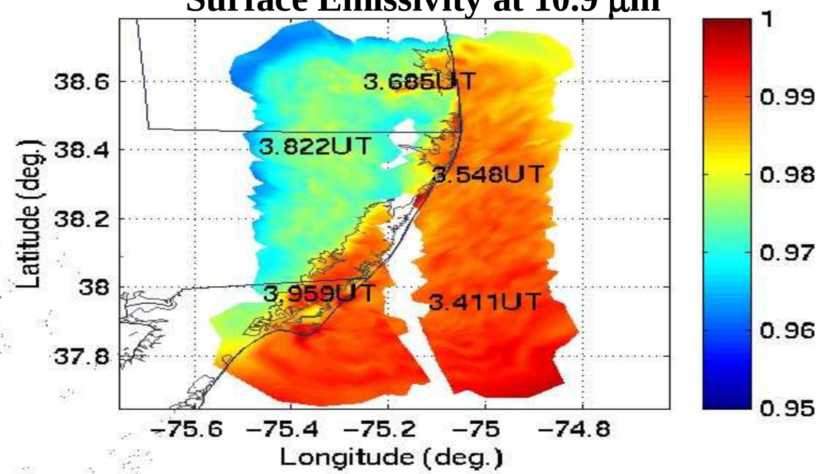


Wallops-98 (June/July, 1998)

Surface Skin Temperature (K)



Surface Emissivity at 10.9 µm



CLAMS (July, 2001)

et al.

Airborne Remote Measurements

- **Provide space and time variations between satellite, radiosonde, ground-based, and other airborne measurements**
  - Ø **Sensor validation**
  - Ø **Geophysical field spatial & temporal characterization**

Proteus aircraft
w/ NAST pod

Proteus NAST pod payload configuration used in some earlier deployments

Enabling Technologies Required for Measurement Concept

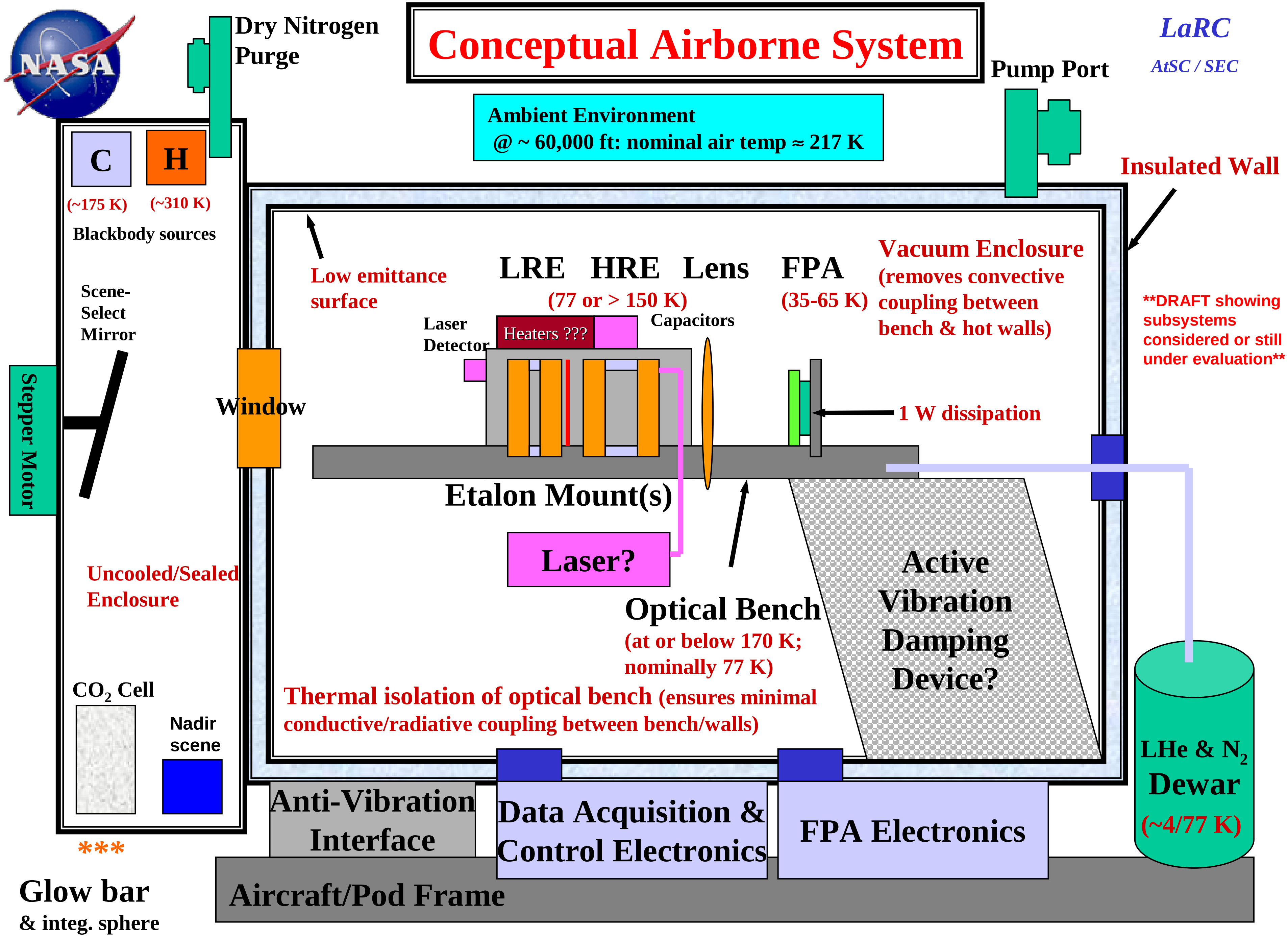
- Three technologies are required for TTSS-FPI within IIP to enable the **spectrally tunable imaging FPI** measurement technique for achieving high-resolution over narrow spectral ranges:

  1) **precision control of etalon plates**
     a) to demonstrate accurate spectral tuning and parallelism control of the LRE and HRE; likely including piezo-electric actuators in a capacitance-based feedback system

  2) **high-sensitivity two-dimensional infrared detector array**
     a) to demonstrate spatial imaging and required SNR; desire advanced materials for higher-sensitivity operation at warmer temperatures, with goal of reducing active cooling requirements in space-based applications

  3) **spectral and radiometric calibration**
     a) to demonstrate spectral registration and absolute intensity fidelity in radiance measurements; requires stable & narrow spectral emission character sources

Conceptual Airborne System



Instrument/System Specifications

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Instrument Parameter[a]	Airborne System[b]
Etalons	
Diameter	**~ 8 cm (6 cm active area)**
Free Spectral Range (HRE, LRE)	**1.52 cm^{-1}, 5.46 cm^{-1}**
Scan Range (LRE/HRE)	**~ 5 / 15 micron**
NB filter	
Transmission characteristics	**3 – 5 cm^{-1} FWHM; $\tau > 50\%$; ~ Gaussian shape; 7 – 12 cm^{-1} FW 5%**
FPA	
Format	**160x160 (~40x40, effective)**
Pixel Size	**60 µm x 60 µm (~240 x 240 eff.)**
Operating Temperature	**35 – 65 K**
Effective D*	**~ 9.0 E^{12} cm $Hz^{1/2}$/W**
Overall System	
Optical System Peak Transmittance	**~0.35**
Effective System Finesse	**~ 20**
Spectral Resolution	**0.068 cm^{-1}**
Spectral Range	**~ 1053.5 – 1056. cm^{-1}**
f/#	**~ 3.0**
Spatial Resolution	**~13 m (~52 m, eff.), ~2.1 km across FPA**
Dwell Time per Spectral element	**~0.26 s**
Dwell Time per Spatial Sample	**16 s for spectrum (~ 60 elements)**
Coverage Time	**1.76 km along a/c track in 16 s**
Platform altitude	**~ 16 km**
Data rate/storage[c]	**~ 2-20 MB/s / 60 GB (8hrs)**

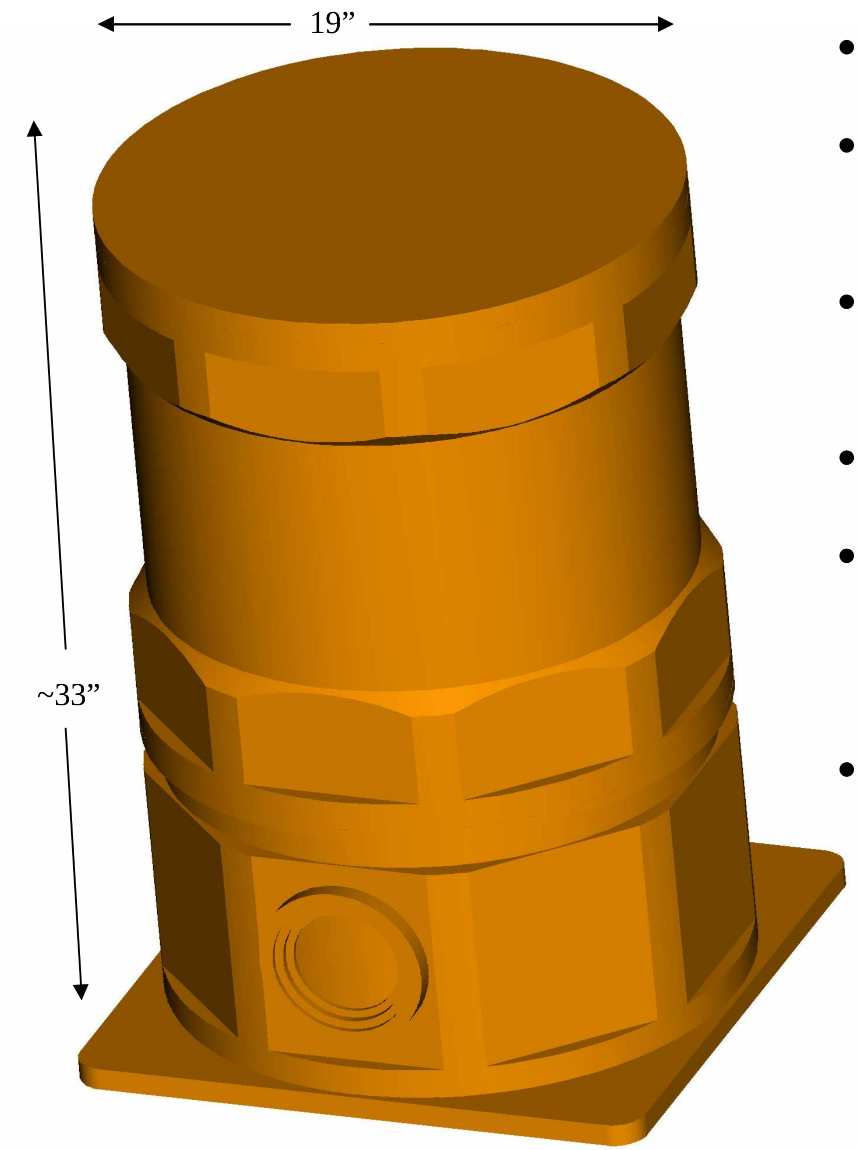
[a] *assumes NESR ~ 0.15 mW m^{-2} sr^{-1} cm*

[b] *nominal parameters desired; actual ones are fcn of obtainable FPA characteristics (i.e., D*, format, pixel size)*

[c] *worst case range; nominal values TBD per frame averaging; further reduction from pixel binning*

CAD Model of Instrument Enclosure

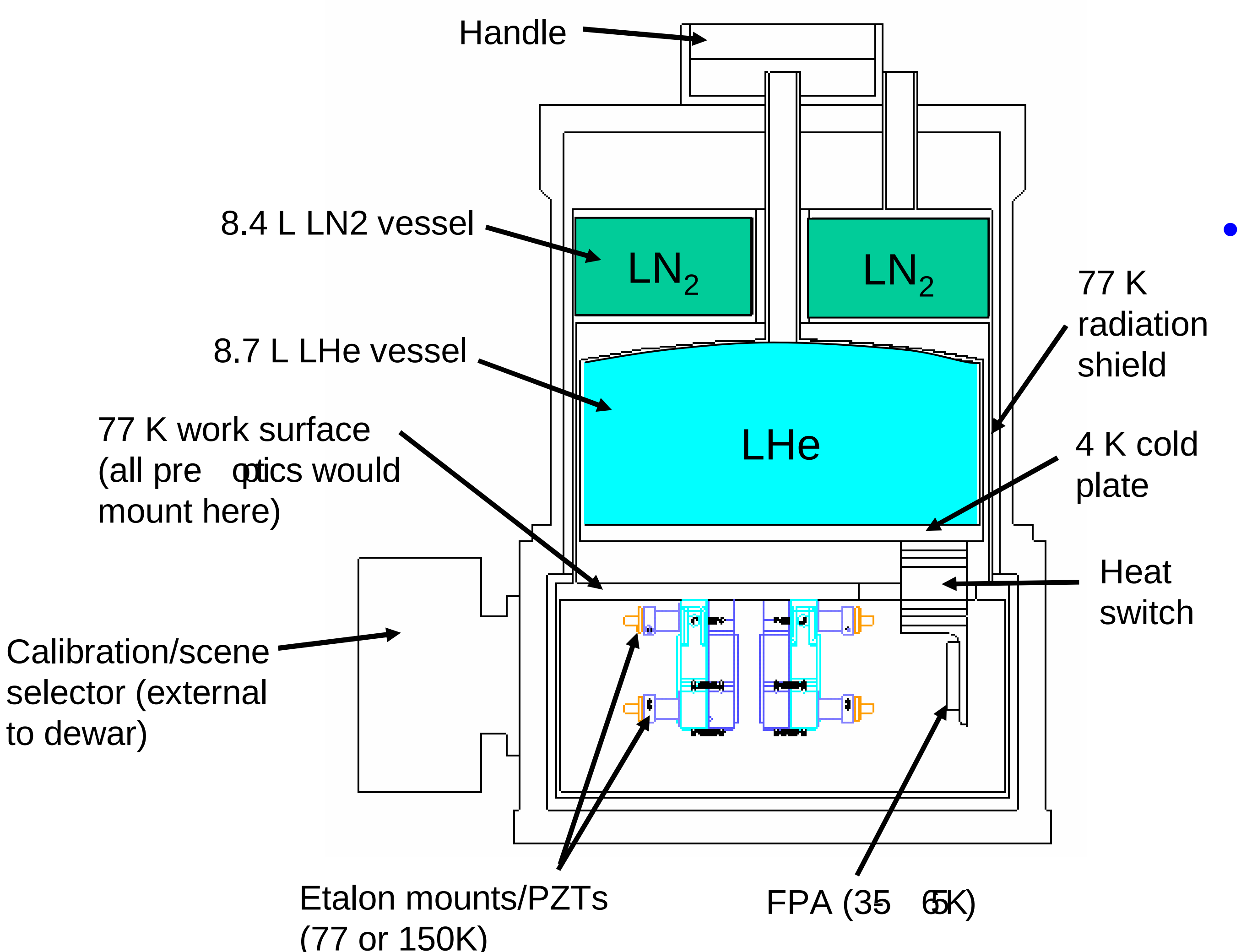
IR Labs Dewar



- Vacuum jacketed dewar
- Liquid helium vessel – Low temperature cooling
- Liquid nitrogen cooled radiation shield – Extends the helium hold time
- Liquid nitrogen cold plate
- Mechanical heat switch and electric button heater provide accurate temperature control of FPA
- Absolute Pressure relief valves and indium seal case gaskets enable high altitude operation

External attachments not shown (e.g., calibration assembly, vacuum flange, and handle)

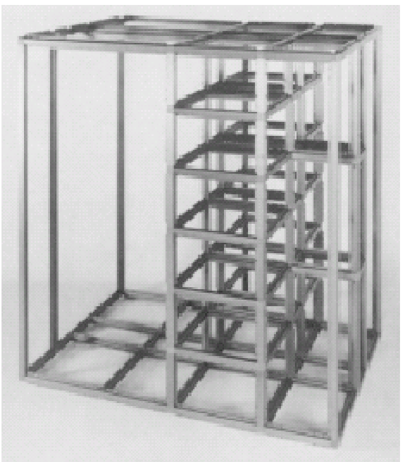
LHe/LN$_2$ Open Cycle Dewar

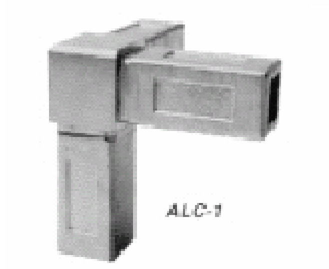


- **Provides instrument enclosure & thermal control during expected 7 hour high-altitude flight duration**

Conceptual Drawing (based upon IR Labs system)

Instrument Rack





Gusseting provides maximum strength for the most demanding applications.

The addition of a simple bolt-on 3/16" (4.76mm) 6061-T6 aluminum gusset provides reinforcement that will meet MIL-STD-810D and MIL-STD-167-1 shock and vibration requirements.

Roll pins *– spring type, corrosion resistant steel roll pins (MS171526) can be used with standard locking clips to provide a simple method of reinforcing the joint against axial strains in excess of 1,600 lbs. (725.76 kg).*

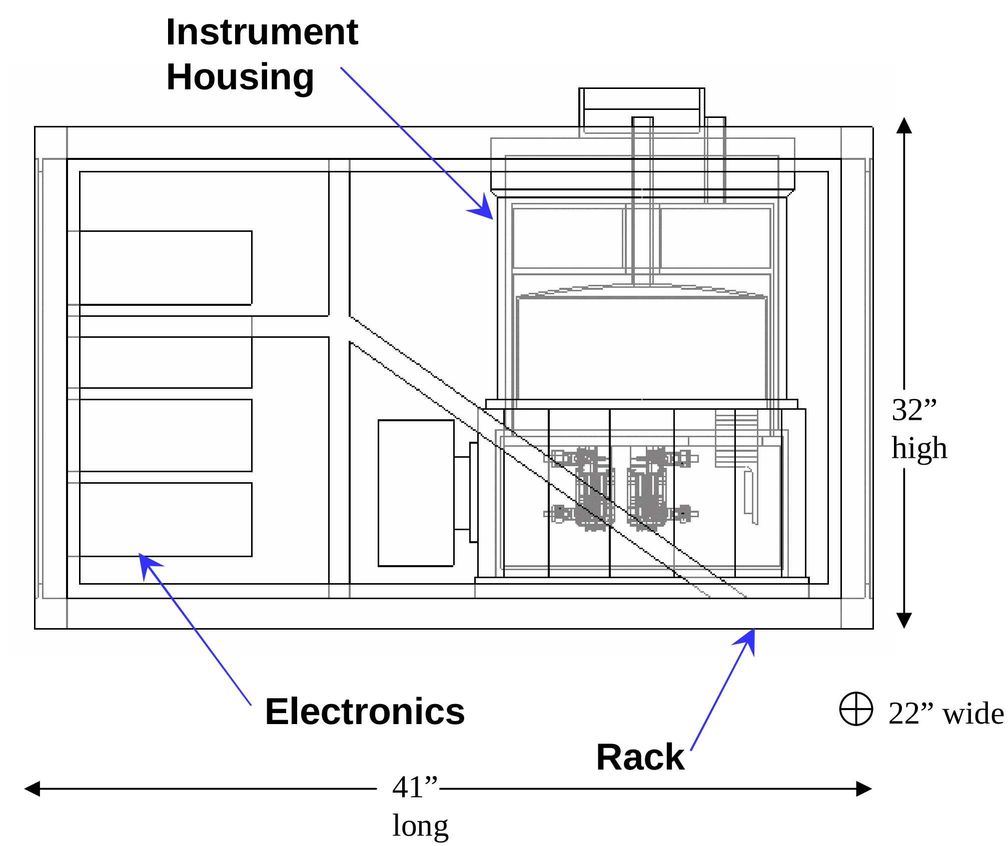
End caps *– black butyrate plastic caps fit into end of extrusion to close/seal tubing.*

Locking/non-locking clips *– 21 GA. 0.032" (0.81 mm) 1075 SAE soft spring steel clips (CAD plated per MIL-spec QQ-P-416 class 3 type II) are seated between the casting and extrusion for permanent or temporary assembly.*

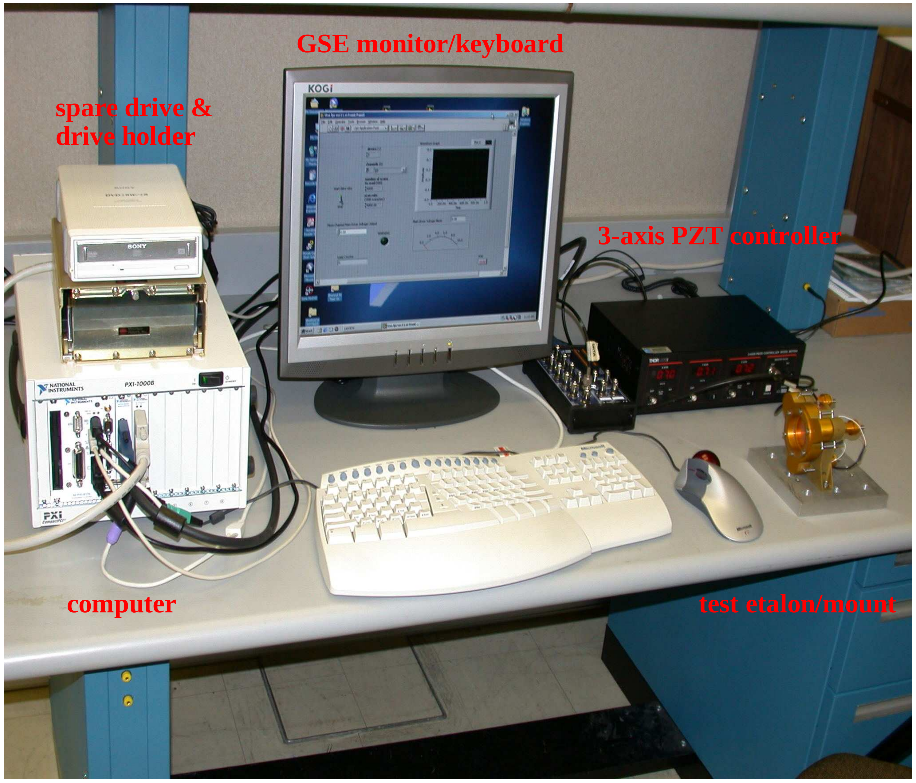
NOTE: Locking clips will be provided with each order unless non-locking clips are specified.

Aluminum panels *– 1/8" (3.18mm) thick 6061-T6 flat panels are available in 19" (482.60mm) panel widths as standard. Vertical heights of 1 23/32" (43.65mm) to 20 31/32" (532.60mm). Other sizes available upon request per your specification.*

Øaluminum castings and extrusions available from Amco Engineering company



Flight Computer



- **To enable autonomous operation (instrument control and data sampling, binning, and storage)**
- **FPA + housekeeping (temps., time, gps, I/O, etc.) data rate ~ 20 MByte/sec; data storage for single flight (8 hrs) ~ 60 Gbyte**
- **Control of etalon plate separation to ~0.3 um resolution with step settle time of less than ~25 mSec**

computer system = **National Instruments 1.26 GHz 8176 Pentium III & associated I/O cards**

[NI 8176 RT "real-time" processor can be borrowed from another project should precise interface timing be required]

512 MB RAM, 20 GB storage (standard), + 73 GB external flight capable HD

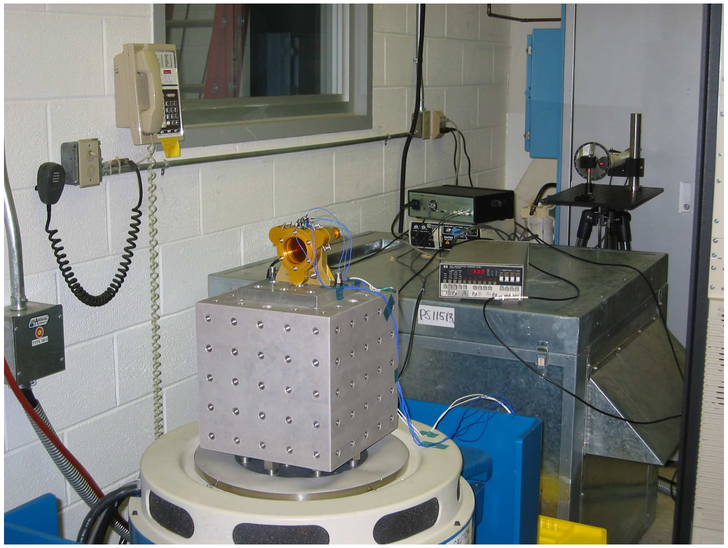
Flight software: Labview (NI proprietary) + NASA/LaRC C code as needed

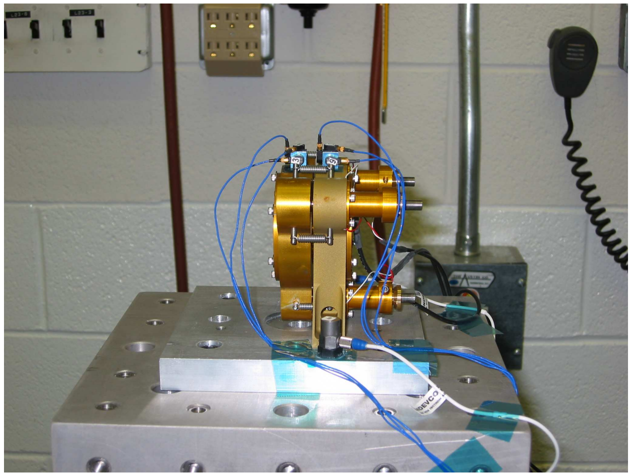
Etalon Test Fixture

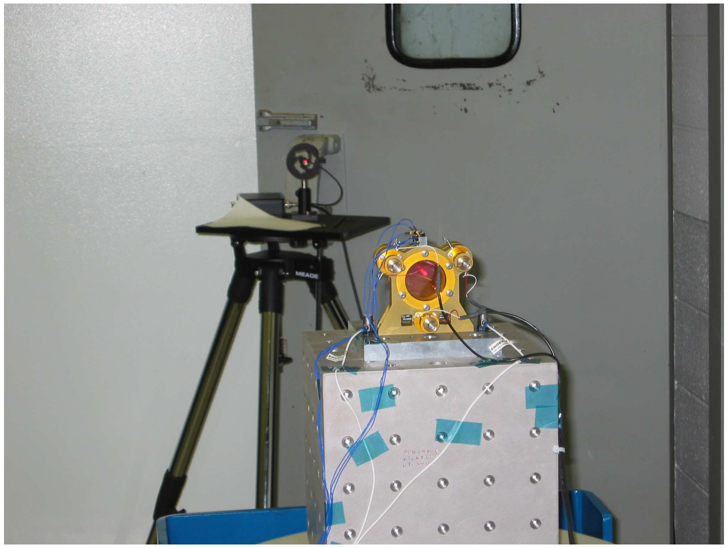
- **Developed to verify flight etalon mount design**
  - **secure etalons without optical distortion while under aircraft vibration environment**
  - **enable PZT control of etalon plates**

Etalon Test Fixture: Vib Test

- **Preliminary vibration test at LaRC**
  - **Vibrated @ and slightly above nominal flight levels while observing HeNe fringe pattern**
  - **Fixture remained intact/aligned post-event**
  - **One axis never lost fringes, other 2 produced unacceptable motion**
  - **This preliminary test represents worst-case scenario, without etalon control and instrument/aircraft interface isolation**
  - **Will be repeated in more-realistic configuration when possible**







Status and Near-Term Activities

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- Instrument concept, system, and enabling subsystems defined
- FPA acquired; etalon & NB filter requirements specified and procurement underway
- Mechanical design/modeling for instrument skeleton (e.g. enclosure & optical bench) and enabling subsystems (e.g. etalon mounts, scene selection mirror assembly, & anti-vibration system) in progress; A test etalon mount fixture was fabricated, assembled, and vibration tested; conceptual instrument/aircraft interface formulated; multiple platform/pod capabilities will be accommodated w/o change in design path (i.e., to allow flight in the NAST Proteus pod, the ER-2Q bay, and a new pod being developed for DFRC (by Scaled Composites) for NASA payload use on Proteus)
- Thermal modeling studies performed to evaluate different environmental control methodologies (i.e. active vs passive, vacuum vs purge) and quantities of required expendables (such as lN2/lHe) during nominal flight periods; dewar for thermal control and instrument enclosure under procurement
- A preliminary electrical design for data acquisition/storage and instrument control (e.g. FPA readout and PZT drive/feedback electronics) is being formulated, and will be vib-tested in lab; A design for the etalon control system has been completed. Breadboard of the signal conditioning electronics has been built and tested. Development of a printed circuit board layout has been completed; laboratory testing underway.
- NAST pod environmental (thermal/vibration) characteristics under evaluation, helping to define insulation/isolation and control requirements
- Calibration subsystem methodology and etalon control system definition in progress

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- Airborne flight-ready instrument expected ~ Jul/04

Summary

- **Tropospheric ozone is a HIGH-PRIORITY measurement in the NASA OES Strategic Enterprise and Science Research Plans**
- **TTSS-FPI concept enables new multispectral imaging measurement capability for space-based observation of tropospheric ozone**
- **Exploits spatial and temporal benefits of GEO-imaging (e.g. monitoring of regional pollution episodes)**
- **Instrument concept and technologies also have broad-based applicability to measurement of other geophysical parameters (passive & active)**
- **Hybrid instrument implementations (e.g. FPI + FTS) can greatly simplify sensor designs where high spectral resolution is needed in only select spectral regions**
- **Airborne instrument system (TTSS-FPI) under development within NASA's IIP to demonstrate from an airborne platform an advanced atmospheric remote sensor concept intended for geostationary-based measurement of tropospheric O_3**